Is it possible to describe short-range NN correlations in nuclei on the basis of nucleonic degrees of freedom only ?

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Abstract

Assuming that NN interaction is modified inside a nucleus by a specific way, phenomenological effective broad core (BC) NN potential is constructed. It is shown that increase in the width of repulsive core lets us describe the Coulomb form factors of few-body nuclei on the basis of nucleonic degrees of freedom only.

I. INTRODUCTION

In the last years, microscopic calculations of the lightest nuclei ($A \leq 4$) on the framework of nonrelativistic quantum mechanics have achieved a high accuracy. It becomes apparent that the classic approach built around two-body potential for free nucleons and nucleonic degrees of freedom only does not explain many important properties of the nuclei. More sophisticated approaches developing recently have a number of refinements going beyond a traditional scheme. They are strongly interrelated if more general theory (QCD) is consistently used from the beginning. But in real calculations in nuclear physics three general types of the refinements can be presented:

1. Modification of interaction between the nucleons in nuclei through changing of the pair-wise NN forces themselves and generation of the multi-nucleon forces.

2. Consideration of non-nucleonic degrees of freedom (meson, Δ-isobar, quark-gluon etc.).

3. Consistent relativistic description of the process involved.

Just corrections of the first type attract a particular attention because they can be done in terms of traditional computational scheme. It is not surprising that the various models of 3N forces are very popular for solution of the problems in the theory of few-body systems (for example, the underbinding of 3- and 4-nucleon systems [1]). However, some problems can not be explained on the framework of pure nucleonic degrees of freedom even if the 3N forces are taken into account. One of the best known example is a manifestation of strong short-range NN correlations in the Coulomb form factors of ^{3}H, ^{3}He and ^{4}He (see, for example, [1–4]).

To explain the short-range correlations in few-body systems the other types of refinements are invoked. Many calculations [1–3,5] show that the contribution of two-body meson exchange currents (MEC) can explain form factors of three- and four-nucleon systems. However, there are some limitations and open problems in such explanation.

Strange as it may seem, a weak point in modern nonrelativistic approaches is the consistent description of deuteron structure. The recent experiments for the measurements of T_{20} polarization [6] have allowed to extract experimentally $C0$ form factor of the deuteron. It turns out that the theoretical consideration of the charge current with MEC (where all ingredients of meson exchanges are the same as in the case of three-body system) destroys the description of the deuteron charge form factor obtained in the impulse approximation [7,8]. Thus, the present calculations are not yet able to simultaneously explain the data for two- and three-body charge form factors on the equal ground [8].

The next problem is that the high values of cutoff masses Λ described meson-nucleon vertexes must be used to explain a large magnitude of two-body exchange currents in three-body form factors, that is in contradiction with modern nucleon structure calculations (see, for example, [9–11]). Besides, very high contribution of MEC to the charge form factor at moderate momentum transfer seems to be hardly consistent to the common practice in nuclear theory (Siegert theorem). It is well known that MEC presents a relativistic

correction to the charge one-body current by the same order of magnitude as the relativistic correction to the wave function itself. Therefore, the consistent relativistic description of NN interaction, few-body wave function and the process of interest is required if the contribution of MEC (in particular the isoscalar one) is large. This conclusion is strongly supported by the recent study of two-body system in relativistically covariant approaches. As was shown in [12–14], the relativistic description of two-nucleon system considerably changes its electromagnetic properties and reduces substantially the contribution of MEC to the charge form factor of the deuteron [12].

It is believed that just the modification of the nucleon interaction inside the nuclei makes possible to solve the problem of strong NN correlations more simply. The small influence of 3N forces to the form factors of ^{3}H and ^{3}He in the earlier calculations (see, for example, [3]) is probably connected with dominantly long-ranged structure of these semiphenomenological forces. It would appear natural that the modification of the short-range part of interaction is essential to improve the description of form factors at moderate and high momentum transfer. Consistent microscopic calculations [15,16] actually show that the main long-ranged components of 3N forces are canceled and, along with it, the shorter ranged forces arise (which, however, have an uncertain parameter [15]).

This work consists in an attempt to explain the charge form factors of the lightest nuclei by the phenomenological modification of NN interaction only. The general description of the model is given in Section 2. The results and discussion are presented in Section 3.

II. THE MODEL

As was mentioned above, NN interaction in nuclei is changed (see also discussion in [17,18]) comparatively to the "vacuum" case.

The aim of this work is to study the possibility of description of short-range NN correlations in the lightest nuclei by the phenomenological modification of NN potential only.

The main features of this scheme are the following:

1. The modification of pair-wise NN interaction only is considered. By this means true multi-nucleon forces are beyond the scope of the paper. This assumption seems to be justified here because the effects from true multi-nucleon forces are hardly separated in such integrated characteristics as charge density of a nucleus. In addition a lot of new parameters in the general case results in great uncertainty in phenomenological analysis.

2. It is suggested that the interaction is modified inside the nuclei so that the low-energy NN phase shifts do not change practically relative to free-nucleon case. In other words, the common "power" of interaction is kept a little affected in nuclei in our model. Indirect evidence that similar situation can be realized in reality presents microscopic study of three-body modification of free NN forces. Thus, in [19] was shown that many components of tree-nucleon forces are canceled in consistent approach, so that overall effect of such modification for the binding energy of ^{3}H is very small. On the other hand, just the modification of "high"-energy part of two-body interaction leads to the significant changes of the properties connected with high momentum transfer that is the most important for our consideration.

3. Since an aim of the paper is the qualitative study of the problem, the model is restricted to the simplest case of pure central NN potential. It is known [20,21] that this simplification does not change significantly the properties of interest for us, in particular, the charge form factor F_{ch} and the root mean squared radius $(r^2)^{1/2}_{ch}$, because the role of non-central components in the corresponding matrix elements is small (there is no transition from S to D components of the wave function). This restriction, however, does not make us possible to investigate the transversal $M1$ form factors of two- and tree-body systems because the interference between $S-S$ and $S-D$ transition in the matrix elements is of primarily importance for these observables [1,4].

Similar type of simplified (effective) potentials is widely used in the microscopic calculations [22] of nuclear properties in such approaches as Resonating Group Method (RGM),

Generator Coordinate Method (GCM) , Hartree-Fock model (HF) etc. These forces are called effective to stress that some effects from the nuclear medium are already taken into account by their construction. Usually, the NN interaction in such an approach is constructed to fit some properties of few-body systems [20,23] and, may be, nuclear matter too [24]. However, no one from these potentials allows to describe quantitatively Coulomb form factors of tree- and four-nucleon nuclei in the region of its second maxima. The work [25] had the most success. In this work was pointed out that to explain the position of the second maxima of ^{3}He and ^{4}He form factors it should be assumed that the NN interaction has a very wide repulsive core. There are still further reasons for that. For example, it was shown in [21,26] that the "hole" in the nucleon density of ^{4}He is much broader than it follows from the calculations with the realistic NN forces. More strong repulsion (even with accounting the contemporary 3N forces) is needed also to explain the density of nuclear matter in the saturation point [18,9,27]. On the other hand, the theoretical models [28,29] developed to study NN interaction in the nuclear matter really show that the temperature and density plays the role of additional repulsion.

Thus, we try to construct our effective NN forces by the increasing of the width of repulsive core in some "realistic" central potential fitted to the two-body data (for example, in potential like $S3$ from the work [20]). Since the minor role of the NN interaction in the states with odd values of partial angular momentum L in all two-body subsystems for the structure of S-shell nuclei, only potential for the even partial states is constructed.

For the sake of convenience the gaussian parameterization of NN interaction is used:

$$V(X) = \sum_{i=1}^{N} C_i(X) \exp(-\alpha_i(X) r^2) \tag{1}$$

Coefficients C_i and α_i for given spin-isospin configuration X ($X = {}^3E$ or ${}^1E$ in our case) are founded by fitting a set of calculated observables to the experimental data. Since the three-nucleon system is the object of main interest for us, the binding energy B, the root mean squared charge radius $(r^2)^{1/2}_{ch}$ and the charge form factor F_{ch} for ^{3}H is chosen for that. In addition, following arguments given above, the low-energy phase shifts for n-p scattering

and the binding energy for the deuteron are also incorporated in the fitting procedure.

Form factor of the deuteron and the main properties of ^{3}He and ^{4}He are calculated and compared with experimental data after the construction of effective potential.

In the calculation of wave functions of few-body systems the variational method based on the multidimensional gaussian non-orthogonal basis is applied. This method has been proposed in [30] and since that it was widely accepted for the high-precision calculations of many-body nuclear problems (see, for example, [26,31,32] and references therein). The detailed information about the used scheme can be found in [33,34,25] for the tree-body systems and in [25,33] for the four-body one. In the calculation the interaction in the odd two-body states (^3P and ^1P) is considered as equal to zero.

III. THE RESULTS AND DISCUSSION

Our calculations are shown that only a priori "knowledge" of the core width makes possible to construct a desirable potential by fitting procedure in view of numerical instabilities of many-parameter minimization. That is why even indirect information discussed above is of primarily importance.

The derived values of parameters C_i and α_i are given in Table I. Five gaussian parameterization ($N = 5$ in eq. (1)) with a common set of nonlinear parameters for triplet and singlet NN potentials is found to be sufficient to meet all our requirements. It shoul be noted that fixation even low-energy NN phase shifts impose so strong restriction on the constructed two-body forces that the only one real parameter can be considered as relatively free until the information about ^{3}H charge form factor come into play. It is the repulsive core width in NN forces can change validly the two- and many-body charge density at short distances. Therefore, a big number of parameters given in Table I is nothing but consequence of chosen parameterization.

The constructed potential is shown in Fig.1a and Fig.1b by the solid line. One from precise phase-fitted realistic potential (Nijm.II from [35]) in the respective states is shown

by the dashed line. It is very important that the constructed potential has a repulsive core ($r_c \simeq 1fm$) about 1.5–2 times broader than that for the realistic one ($r_c \simeq 0.5 - 0.6fm$). Thus, we will call it further as Broad Core (BC) potential.

It is interesting to note that the use of potential with broad core to fit the low-energy NN phase shifts leads automatically to the appearance of additional repulsive bump at the moderate distances $r \simeq 2.5fm$. This is because the low-energy phase shifts determine some "mean size" of two-body system and for that it is necessary to restrict the attractive well from the side of large distances.

In Figs.2 the phase shifts for the BC-potential in the $^3S_1$ and $^1S_0$ channels are shown. It turns out that in spite of strong modification of NN potential needed to fit charge form factor of ^{3}H it is possible to describe quite well NN phase shifts up to $E_{Lab} \simeq 100\ MeV$. More strong repulsion at the short distances leads to that the calculated phase shifts pass above the experimental points as the energy increases. However, the fixation of low-energy part of NN interaction is found to be sufficient for the rather accurate description of important static properties of nuclei with $A = 2 - 4$.

In Table II the root mean squared charge radii and the binding energies of few-body systems are given. For ^{3}H and ^{3}He the results of calculations with and without inclusion of S'-component (i.e. component with the mixed permutational symmetry) are shown. Just the inclusion of this component into the variational basis leads to the sufficient increasing of the binding energies and makes possible to explain the experimental difference in $(r^2)^{1/2}_{ch}$ and F_{ch} (see below) between the two isomeric three-body nuclei. Such high role of the mixed symmetry configurations (with the weight $P \simeq 1.4\%$) is connected with the strong difference between the NN forces in ^3E and ^1E states (especially in the width of repulsive core).

In Figs.3 the charge form factors of ^{3}H and ^{3}He are compared with the new experimental data [4]. It is interesting to note that the S' component leads to the increasing of ^{3}He form factor and, respectively, to the decreasing of ^{3}H form factor in the region of their second maxima. As a result, the quality of description of both form factors is very high in spite of that the only ^{3}H form factor has been fitted.

The calculation of ^{4}He structure was done in the basis of symmetric component only. Therefore, the accurate binding energy for BC-potential is somewhat higher than that given in Table II. At the same time, it is believed that both charge root mean squared radius and form factor of ^{4}H is described rather accurate in this truncated basis because, in this case, the number of protons is equal to the number of neutrons.

The Coulomb $C0$ form factors of the deuteron and ^{4}He (the information about which was not used under the construction of BC-potential) are shown in Fig.4a and Fig.4b. The ^{4}He form factor is in a quite good agreement with experimental data [36] at the wide interval of momentum transfer except the range of second maximum. This fact may be interpreted as that the role of fourth particle to the modification of NN interaction is considerably less than the third one (or, in other words, the relative smallest of $4N$ forces). The description of the deuteron form factor is good up to $q^2 \simeq 10\ fm^{-2}$. For the higher momentum transfer the theoretical curve lies above the experiments. This result seems to be quite reasonable because the effective NN potential is used in the calculation.

It is very interesting that all Coulomb form factors for ^{2}H,^{3}H,^{3}He and ^{4}He calculated in impulse approximation for BC-potential are in a perfect agreement with those for realistic NN forces calculated with inclusion of MEC [7,2]. Thus, the modification of free NN potential in the presence of the others nucleons results in the similar modification of nuclear charge density as that one produced by the meson exchange currents. This agreement seems to be not casual because the same meson exchanges result both in NN forces and in two-body charge density. That is why the theoretical predictions for the different nuclear forces (provided the same input information — NN phase shifts) are closed together if considered in a consistent manner with all meson exchanges [4].

To make the comparison of the calculated results with experimental data more correct it is important to consider the contribution of two-body exchange currents in proposed approach too. If two-body term remains dominant in the second maxima of charge form factors of few-body systems as before then the agreement with experiment will break down. Fortunately, this is not the case. Our estimations show that the absolute magnitude of MEC

reduces by the using of BC potential as compared with the calculations used realistic NN forces. The reason is that the contribution of MEC is defined as some integral from the short-ranged Yukawa function [5,37]: $Y_1 = (1+x)\exp(-x)/x$, where $x = \mu r$, and μ is the mass of corresponding meson. As a result, the magnitude of two-body current drops with the rising of "hole" in two-body wave function at short distances. Such effect was shown in the calculation with phenomenological wave function written in correlated form [5,37]:

$$U = N_S \prod_{k<l} \left(1 - \exp(-\gamma^2 r_{kl}^2)\right)^{1/2} \cdot \exp\left(-\alpha^2/2 \sum_{m<n} r_{mn}^2\right) \tag{2}$$

In that case the magnitude of MEC at moderate momentum transfer in three- and four-body charge form factor decreases with the parameter of two-body correlation γ. As to the real calculations with BC-potential, so, for example, the contribution of MEC to the region of second maximum for charge form factors of three-body nuclei decreases of about 1.5 times relatively to that for realistic NN potentials [2,5]. As the one-body part of charge form factor at second maximum in our approach is strongly increased (see Figs.2) so the relative importance of two-body current (even calculated with standard parameterization of meson-nucleon vertexes, see below) is greatly reduced.

What is more, there is another source of reducing of meson-exchange contribution to the charge density. As was mentioned above, modern nucleon structure calculations (see, for example, [9–11]) obtain much lower meson scales than ordinary used to fit two- and few-body data. This fact presents a good argument in support of developed model. On the one hand, just the decrease in cutoff masses Λ (in particular $\Lambda_{\pi NN}$) in one-boson exchange model [9] leads to the increasing of repulsive core in NN potential. On the other hand, soft πNN form factor ($\Lambda_{\pi NN} = 0.6-0.8$GeV instead of $\Lambda_{\pi NN} \simeq 1.2$GeV commonly used in the calculations) results in pronounced reduction of two-body contribution to the electromagnetic form factors of the lightest nuclei. Thus, in the proposed approach, magnitude of MEC can be considered as a correction to the nonrelativistic one-body charge current up to high momentum transfer. This situation seems to be much favorable than that one in the few-body calculations with realistic NN forces of standard type.

The proposed modification of NN potential is quite similar to that one obtained in the ref. [28]. In this work the calculation of NN potential coming from the exchange of one σ- or ω-meson, inside nuclear matter (in σ-ω model of Walecka [38]), taking into account vacuum polarization effects was performed. The increasing of the core width at small distances and generation of Friedel-like oscillations at large ones was found as a consequence of finite nuclear density. It should be noted that these oscillations [39] are rather common phenomena in the fermion systems. Recall, that the additional oscillation in BC-potential at the distance $r \simeq 2.5\ fm$ arises in our approach as a direct consequence of the broadening of the core to compensate changing of the low-energy NN phase shifts. The position and the magnitude of this bump is in agreement to that found in [28]. At the same time, it is evident that the details of effective potentials at higher distances ($r \geq 3-4\ fm$) can not be reconstructed accurately from the phase shifts fitting. Therefore, the consistent microscopic description only will be able to derive the accurate behaviour of effective NN potential at this range.

IV. CONCLUSION

An attempt to solve some problems of description of strong NN correlations by the modification of NN potential inside the nuclei is done in the paper. Our analysis shows that the increasing of the width of repulsive core makes it possible to describe naturally the strong short-range correlations in nuclei. On this ground an effective central broad core NN potential fitted to the low-energy S-wave n-p phase shifts is constructed. It is shown that this potential makes it possible to describe quantitatively the charge form factors of the few-body systems. The attractive feature of the model is the pronounced reduction both the relative and absolute contribution of MEC to the charge form factors of the lightest nuclei. It is of interest to expand the approach by taken into account the non-central components of NN forces and to include into consideration the odd two-body partial states. It will permit to study the magnetic form factors of few-body systems and the properties of nuclear matter.

Obtained modification of NN potential is in agreement with the qualitative prediction

of ref. [28] and with the small values of cutoff masses in the meson-nucleon vertex form factors [9–11]. At the same time, the proposed approach is phenomenological. It is of primarily importance to investigate quantitatively the nucleon-nucleon interaction in nuclei on the basis of consistent microscopic approach. It is evident that the potential derived, for example, from quark-gluon dynamic must have much more complicated structure. In particular, strong nonlocalities, energy and momentum dependence, non-central and many-body terms inevitably arise in the accurate microscopic consideration. However, there is a reason to hope that the main features of NN interaction inside the nuclei (especially the broadening of repulsive core) are correctly mentioned in the work.

The constructed potential results in the best description of many aspect of structure of the lightest nuclei amongst the known effective potentials. It turns out that it can be successfully used in the microscopic approaches like RGM to accurate account of the short-range correlations in more "heavy" nuclei than those are considered in the paper.

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TABLES

TABLE I. Parameters C_i (in MeV) and α_i (in fm^{-2}) of BC-potential given in eq.(1) for ^3E and ^1E states.

i	1	2	3	4	5
$C_i(^3E)$	1067	3530	–3595	1475	–553.6
$C_i(^1E)$	1416	3309	–3499	1175	–392.4
α_i	5.391	1.197	0.7368	0.3602	0.2651

TABLE II. Binding energies B (in MeV) and root mean squared charge radii $(r^2)_{ch}^{1/2}$ (in fm) of few-body nuclei. S and S' denotes the choice of variational basis in pure symmetric form (S) or as a state with mixed permutational symmetry (S').

	^{2}H	^{3}H	^{3}He	^{4}He
$B(S)$	2.225	7.5	6.8	26.2
$B(S+S')$		8.9	8.2	
$B(exp.)$	2.225	8.48	7.72	28.3
$(r^2)_{ch}^{1/2}(S)$	2.14	1.85	1.87	1.64
$(r^2)_{ch}^{1/2}(S+S')$		1.75	1.89	
$(r^2)_{ch}^{1/2}(exp.)$	2.10	1.76	1.95	1.67

Figure 1. (a) The NN potential in $^1S_0$ partial state. The BC-potential is plotted by solid line, the realistic Nijm.II potential is plotted by dashed line. (b) The same as in Fig.1(a) for $^3S_1$ partial state.

Figure 2. Triplet ($^3S_1$) and singlet ($^1S_0$) n-p phase shifts for BC-potential.

Figure 3. (a) The charge form factor of ^{3}H calculated in the impulse approximation for BC-potential in the pure symmetric basis (dashed line) and in the complete basis (solid line). (b) The charge form factor of ^{3}He.

Figure 4. (a) C0 form factor of ^{2}H calculated for BC-potential in the impulse approximation. (b) The charge form factor of the ^{4}He.